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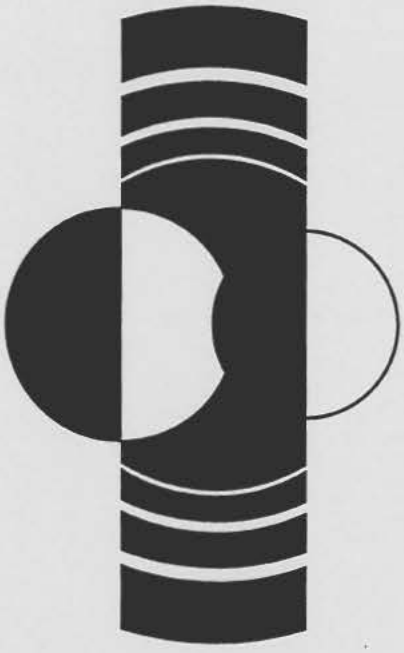

ABSTRACTS

IN SITU RESOURCE UTILIZATION (ISRU II) TECHNICAL INTERCHANGE MEETING

November 18–19, 1997

Lunar and Planetary Institute
Houston, Texas

IN SITU RESOURCE UTILIZATION (ISRU II) TECHNICAL INTERCHANGE MEETING

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Lunar and Planetary Institute
Houston, Texas

Convened by
David Kaplan, NASA Johnson Space Center
R. Stephen Saunders, Jet Propulsion Laboratory

Sponsored by
National Aeronautics and Space Administration
Lunar and Planetary Institute

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PREFACE

This volume contains abstracts that have been accepted for presentation at the In Situ Resource Utilization (ISRU II) Technical Interchange Meeting, November 18–19, 1997, at the Lunar and Planetary Institute, Houston, Texas.

Logistics, administration, and publication support for this meeting were provided by the staff of the Publications and Program Services Department at the Lunar and Planetary Institute.

AGENDA

Tuesday, November 18, 1997

7:30 a.m.	REGISTRATION AND CONTINENTAL BREAKFAST
8:30 a.m.	WELCOME AND INTRODUCTION
9:00 a.m.	Connolly J. F.* *HEDS Strategy for Robotic Mars Mission*
9:30 a.m.	Stancati M. L.* Niehoff J. C. Jacobs M. K. German D. *Mars In Situ Propellant Production (ISPP) Assessment*
10:15 a.m.	BREAK
10:45 a.m.	Zubrin R.* Kito T. Frankie B. *Report on the Construction and Operation of a Mars In Situ Propellant Production Unit Utilizing Reverse Water Gas Shift*
11:15 a.m.	Lawless W. N.* *Oxygen Extraction Using a Ceramic Honeycomb Technology*
11:45 a.m.	Hu H.* Yadav T. *Intermediate-Temperature Electrolysis Cells for Oxygen Production from Carbon Dioxide*
12:15 p.m.	LUNCH and MIST Facility Tour
1:45 p.m.	Wiens R. C. Cremers D. A. Blacic J. D.* Funsten H. O. Nordholt J. E. *Stand-Off Planetary Surface Analysis Using Laser-induced Breakdown Spectroscopy and Laser-induced Plasma Ion Mass Spectrometry*
2:15 p.m.	Agresti D. G.* Wdowiak T. J. Mirov S. B. Kudryavtsev A. B. Kinney T. R. *In Situ Resource Assessment and Process Control with Laser Raman Spectroscopy*
2:45 p.m.	Cooper B. L.* McKay D. S. Allen C. C. Hoffman J. H. Gittleman M. E. *Characterization of the Resource Potential of Martian Soil Using the Integrated Dust/Soil Experiment Package (IDEP)*
3:15 p.m.	BREAK
3:45 p.m.	Mueller P. J.* Rapp D. *Hydrogen Transport to Mars Enables the Sabatier/Electrolysis Process*
4:15 p.m.	Lin F. N.* Bollo T. R. Peterson D. M. *Oxygen Liquefaction and Zero-Loss Storage System*
4:45 p.m.	Fenner J. E.* Edman K. A. *Gas Generation and Cryogenic Refrigeration Technologies*
5:15 p.m.	WRAP-UP
5:30 p.m.	ADJOURN
6:30 p.m.	DINNER AT A LOCAL RESTAURANT

Wednesday, November 19, 1997

8:00 a.m.	REGISTRATION AND CONTINENTAL BREAKFAST
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8:45 a.m.	Jakeš P.* *Microtel: A TV Microscope for Planetary Field Geology and Resource Evaluation*
9:15 a.m.	Drake D. M.* Clark B. C. Jakosky B. M. Reedy R. Squyres S. W. *A LiF Silicon Sandwich Counter to Measure Water Content of Planetary Surfaces*
9:45 a.m.	Marshall J.* Koppel L. Bratton C. Metzger E. Hecht M. *In Situ Identification of Mineral Resources with an X-Ray-Optical "Hand-Lens" Instrument*
10:15 a.m.	BREAK
10:45 a.m.	Gorevan S.* Rafeek S. Myrick T. Kong K. Y. Mahaffey P. *Minaturized Material Sampling and Transfer Devices for Extraterrestrial Exploration*
11:15 a.m.	Finn J. E.* Sridhar K. R. *In Situ Generation of Carrier Gases for Scientific Analyses on Mars*
11:45 a.m.	LUNCH
1:30 p.m.	Wegeng R. S.* TeGrotenhuis W. E. Tonkovich A. L. Y. *In Situ Propellant Production Based on Micro Chemical Systems*
2:00 p.m.	Vuskovic L.* Ash R. L. Popovic S. Dinh T. Van Orden A. *Oxygen Production and Separation from Martian Atmosphere by the Radio-Frequency Discharge*
2:30 p.m.	Bruckner A. P.* Coons S. C. Williams J. D. *Feasibility Studies of the Extraction of Water Vapor from the Martian Atmosphere by Adsorption in Zeolite 3A*
3:00 p.m.	BREAK
3:30 p.m.	Johnson S. W.* Chua K. M. *Engineering Properties of the Regolith on the Moon and Mars Related to ISRU*
4:00 p.m.	Kaplan D. I.* *Mars ISPP Flight Demonstration: A Status Update*
4:30 p.m.	WRAP-UP
4:45 p.m.	ADJOURN

CONTENTS

IN-SITU RESOURCE ASSESSMENT AND PROCESS CONTROL WITH LASER RAMAN SPECTROSCOPY. D. G. Agresti[1], T. J. Wdowiak[1], S. B. Mirov[1], A. B. Kudryavtsev[1], and T. R. Kinney[2], [1]Astro and Solar System Physics Program, Department of Physics, University of Alabama at Birmingham, Birmingham, AL 35294-1700, [2]Control Development Inc., South Bend, IN 46619.

For in-situ resource utilization certain tasks must be accomplished, including prospecting for available resources and process monitoring and control. During prospecting, surface materials are identified as to whether they contain mineral or molecular components needed for the anticipated process; then ores are found in which these materials are most concentrated. Following size reduction and/or pulverization, raw materials are transported and introduced into the processor unit, where intermediate and final products are analyzed to ascertain that the production process is proceeding as desired. With continual monitoring of intermediate products, feedback may be employed as part of the control strategy.

For in-situ application, laser Raman spectroscopy is the ideal resource assessment technique for all these tasks. It has the capability to (1) characterize resource minerals in rocks, soils, or ices; (2) prospect for ores by identifying high concentrations of desired resource material; and (3) monitor a production process by characterizing intermediate and final products (solids or liquids). Moreover, the technique has been implemented in a compact instrument suitable for spacecraft use, e.g. on the surfaces of Mars, the Moon, asteroids, etc.

Two years ago, we proposed consideration of laser Raman spectroscopy for incorporation into lander spacecraft [1], having recognized that technological developments had progressed in a number of areas to the point where miniaturization of the typical laboratory configuration became feasible. In particular, these included (1) miniaturized lasers to provide the exciting radiation; (2) fiber-optic wave guides to allow convenient transmission of the exciting and scattered radiation, including over long distances; (3) holographic notch filters, permitting exclusion of the intense, exciting radiation from the collection fiber, and hence the detector; and (4) CCD detector arrays, which permit miniaturization of the detection system, and hence the entire spectrometer.

With support from NASA's Planetary Instrument Definition and Development Program (PIDDP), we have recently completed a (Mark Ia) laser (785 nm) Raman spectrometer measurement system that is adapted, by virtue of its small size, mass, and power requirements, for in-situ use on planetary surfaces. A more sensitive Mark II instrument is under construction.

A typical measurement with this instrument requires seconds or less. To make a measurement, the Raman probe component is placed near (~1–10 mm) the target material. Being comparable in size and shape to a cigarette, the probe can easily be positioned for resource assessment by a manipulator arm attached to a rover or other mobile platform. It can also be incorporated into a production facility for continual process monitoring. With fiber access to multiple Raman probes, and appropriate switching among fibers, all of these functions could be accomplished with a single spectrometer, e.g. used to monitor various stages in the production process.

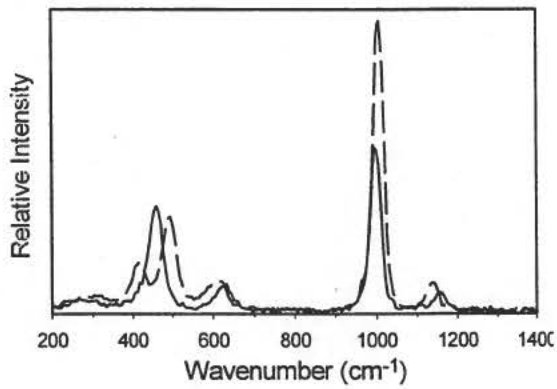

Fig. 1. Representative spectra obtained with our Mark Ia laser Raman spectrometer system, showing its ability to discriminate between minerals. Spectra shown are for the minerals, gypsum ($CaSO_4 \cdot 2H_2O$, dashed line) and celestite ($SrSO_4$, solid line).

In laser Raman spectroscopy, laser radiation illuminates a sample under investigation. The scattered light, which includes a small fraction ($\sim 10^{-6}$–10^{-9}) shifted in wavelength due to quantized energy loss to vibrational modes in the sample, is directed to a dispersive element that functions simultaneously to exclude the intense, unshifted wavelengths from the detector system and to spread the shifted wavelengths so that spectral data may be acquired. Output is in the form of a spectrum (intensity versus energy shift, expressed as cm^{-1}) that exhibits peaks characteristic of contained molecular functional groups or other vibrating units. The peaks, which tend to be narrow, e.g. in comparison to typical IR measurements, have positions (and to a lesser degree, relative intensities) that are highly diagnostic (cf. Fig. 1). The technique can provide useful data on virtually any material in solid or liquid form.

References: [1] Wdowiak T.J. et al. (1995) *LPS, 26*, 1473–1474.

FEASIBILITY STUDIES OF THE EXTRACTION OF WATER VAPOR FROM THE MARTIAN ATMOSPHERE BY ADSORPTION IN ZEOLITE 3A. A.P. Bruckner, S.C. Coons, and J.D. Williams, Aerospace and Energetics Research Program, University of Washington, Box 352250, Seattle, WA 98195-2250; bruckner@aa.washington.edu.

To achieve the maximum benefit from Martian in situ resource utilization (ISRU), an indigenous source of water must be developed. The possibility of obtaining water on Mars would make feasible the operation of a Sabatier/electrolysis (S/E) propellant plant without having to import the necessary seed hydrogen from Earth. This paper presents the results of a continuing feasibility study of the extraction of water vapor by adsorption from the Martian atmosphere.

Water on Mars is scarce. It is present as ice in the polar caps and perhaps as subsurface ice, and it is adsorbed in the regolith, but the atmosphere is the most highly characterized and globally distributed water source on the planet (0.03% by volume).[1] The desire to utilize this atmospheric water led to the development of the Water Vapor Adsorption Reactor (WAVAR) concept.[2,3,4] Past designs for extracting atmospheric water have invoked compression-cooling processes, which require high specific power inputs.[5] Water vapor separation by adsorption has fewer moving parts, and is both less massive and less energy intensive.[2]

WAVAR is conceptually very simple, as can be seen from Fig. 1. Martian atmosphere is brought into the system through a filter by an axial-flow fan. The filtered atmosphere is passed over the adsorbent bed, where the water vapor is removed from the flow by the zeolite molecular sieve. The disk-shaped bed is divided into sectors by insulating separators. Once a sector has reached saturation, it is rotated into a chamber and sealed off from the outside. A microwave emitter is engaged, heating the adsorbent bed sector and driving off the water vapor. The desorbed water vapor is condensed and piped to storage, where it is available for utilization by a S/E propellant production plant or for use by a manned Mars base. The WAVAR design has only six components: a filter, a fan, an adsorption bed, a regeneration unit, a condenser, and a control system. Figure 2 shows a vertical configuration and the dimensions used for the simulations presented here.

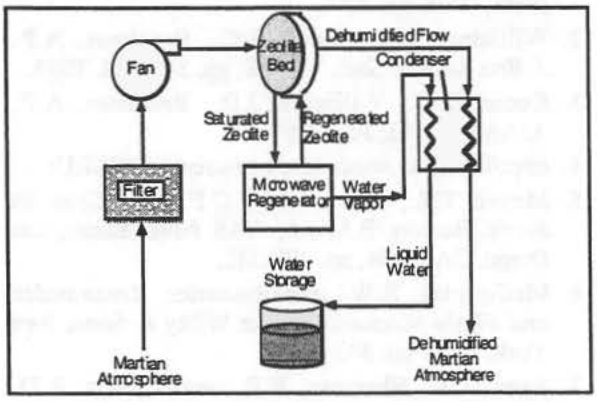

Fig. 1 Schematic of WAVAR, the Water Vapor Adsorption Reactor.

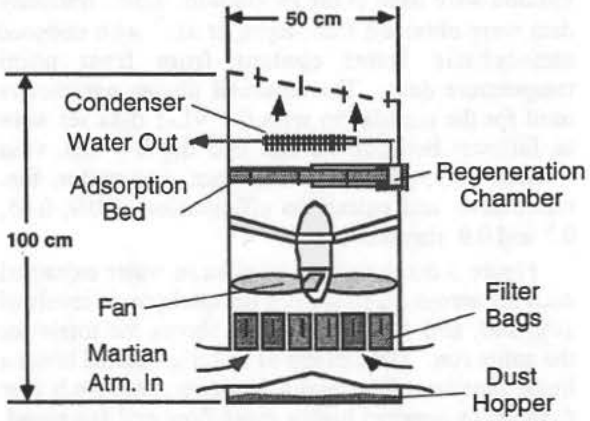

Fig. 2 Vertical WAVAR configuration used for simulation.

For water vapor adsorption on Mars the choice of adsorbent is limited to those with an aperture of 3 Å (slightly larger than a water molecule), such as UOP (formerly Union Carbide) Molecular Sieve 3A. This adsorbent is highly specific to water and is effective at excluding CO_2. The adsorption and desorption characteristics of zeolite 3A were computed using the Dubanin-Polanyi model.[3] For desorption at 6 torr, starting at an ambient temperature of 220 K, the optimum desorption temperature is 420 K and the corresponding specific energy of desorption is 5.48 MJ/kg of water recovered.

Preliminary microwave desorption experiments were performed with saturated 50 g samples of zeolite 3A. Adsorption was done passively, with final loading determined by weight. The samples were then heated and weighed at 10 sec intervals and typical desorption curves were obtained.[3]

The largest power draw in the WAVAR system is that of the fan, and determining its power requires examination of all the pressure drops throughout the system. The two main sources of pressure drop, ΔP, are the filter and the adsorption bed, the latter being dominant. All sources of ΔP are functions of the flow velocity. The pressure drop of the zeolite bed was computed using a linear approximation to the Chilton-Colburn and Colburn-J Factor correlations over the range of Reynolds numbers of interest (5-120).[3] The fan was modeled as a four-bladed

EXTRACTION OF WATER VAPOR FROM THE MARTIAN ATMOSPHERE

A.P. Bruckner, S.C. Coons, and J.D. Williams

propeller with an efficiency of 85%, and its power requirement was found using classical momentum theory.[6]

For a given available power the amount of water collected by WAVAR was computed iteratively, using the expressions for fan power and desorption power, both being dependent on the mass flow rate generated by the fan.

To make a credible determination of the performance of the WAVAR, actual Martian atmospheric water data from the Viking 1 (VL-1) mission were used in the simulation. Local humidity data were obtained from Ryan *et al.*,[7] who deduced atmospheric water content from frost point temperature data. The assumed design parameters used for the simulation with the VL-1 data set were as follows: bed dia. 50 cm, bed depth 4 cm, void fraction 0.33, pellet dia. 3.25 mm, and motor, fan, microwave, and extraction efficiencies of 0.9, 0.85, 0.7 and 0.9, respectively.

Figure 3 displays the variation in water extracted each sol across a 250 sol run for total power levels of 100, 200, and 400 W. Table 2 shows the totals for the entire run. The amount of water produced is not a linear function of the available power, because higher throughput requires higher mass flow and fan speed, and thus higher flow velocity through the bed, which increases the pressure drop losses. The daily rates of water production and the 250 sol totals turned out to be quite low, and the specific energy relatively high compared to our previous results[2] (but still considerably better than for the compression-cooling concept[5]), reflecting the low average humidity of the VL-1 site, lower than the global average of 0.03%.

In our earlier work[2] we had assumed the more optimistic conditions used by Meyer and McKay (0.06% humidity) for their compression-cooling concept.[5] Although such favorable conditions were not observed by either of the Viking landers 20 years ago, this does not preclude their existence. Water is a highly variable component of the Martian atmosphere and is strongly dependent on the season, latitude, and local topography.[1] For example, at high latitudes in the northern hemisphere during summer the humidity is significantly higher than the global average. Also, the recent Pathfinder mission to Mars has returned temperature data warmer than those at the two Viking sites and close to the assumptions made by Meyer and McKay, potentially indicating higher humidity. For every 5 K drop in the frost point temperature the available water is cut roughly in half and quickly becomes minuscule if the frost point drops below about 190 K, as is the case after sol 250 at VL-1.

These considerations highlight the importance of landing site selection for a mission using a WAVAR. If attractive landing sites with frost points in the 200-210 K range are found, then WAVAR has the potential to become an enabling technology for advanced unmanned exploration, as well as to provide supplemental water for the first human colonization of the red planet. Using Mars' atmosphere as a source of water for ISRU remains an attractive option, due to the global distribution of atmospheric water, and because water will be a critical resource for the exploration and colonization of Mars.

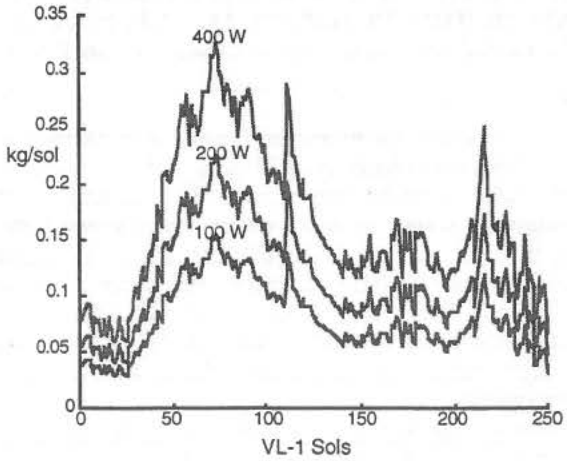

Fig. 3 Water extraction rate, sols 1-250 at VL-1 site.

Table 2 Sol 1-250 simulation results.

	100 W	200 W	400 W
Tot. Energy (kW-hr)	615	1230	2460
Water Extracted (kg)	20	29	41
Specific Energy (kW-hrs/kg)	31	43	60
Avg. Flow Vel. (m/s)	6.1	8.8	12.6
Avg. Motor Speed (RPM)	485	703	1010

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Characterization of the Resource Potential of Martian Soil Using the Integrated Dust/Soil Experiment Package (IDEP). Bonnie L. Cooper[1], David S. McKay[2], Carlton C. Allen[3], John H. Hoffman[4], and Mark. E. Gittleman[5], [1]Oceaneering Space Systems, 16665 Space Center Blvd., Houston, TX 77058-2268, bcooper@oss.oceaneering.com, [2]NASA Johnson Space Center, Houston, TX 77058 david.s.mckay1@jsc.nasa.gov, [3]Lockheed-Martin Space Missions Systems and Services Company, 2400 NASA Road One, Houston, TX 77058, callen@ems.jsc.nasa.gov, [4]The University of Texas at Dallas, PO Box 830688, Richardson, TX 75083-0688, jhoffman@utdallas.edu, [5]Oceaneering Space Systems, 16665 Space Center Blvd., Houston, TX 77058-2268, mgittlem@oss.oceaneering.com

The Integrated Dust/Soil Experiment Package (IDEP) is a suite of instruments that can detect and quantify the abundances of useful raw materials on Mars. We focus here on its capability for resource characterization in the martian soil; however, it is also capable of detecting and quantifying gases in the atmosphere. This paper describes the scientific rationale and the engineering design behind the IDEP.

Introduction of moisture to Mars soil may liberate copious oxygen. It has been proposed[1] that abundant crystal defects in the Mars soil grains may be the site of concentrated oxygen that can be liberated by either water vapor or ice. The IDEP has the potential of showing whether oxygen can indeed be released from martian soil when it is exposed to water.

The IDEP also measures the reaction of martian soils to hydrogen. Laboratory experiments have shown that oxidized iron-bearing phases are easily reduced by hydrogen[2]. Consequently, the reduction of these oxides and hydroxides by hot hydrogen may prove to be a ready source of water. In future applications, the water could be electrolyzed and the hydrogen recycled so that the primary product becomes oxygen. Such a process must compete with extraction of oxygen from the martian atmosphere, but it is not obvious that the atmospheric extraction is more efficient, requires less energy, or is more reliable. Data on actual Mars soils is clearly needed to make a credible tradeoff, and our instrument package will provide such new basic data.

Another potentially useful process that may be identified by our experiment package is the conversion of potential Mars carbonates to oxide or lime, the key ingredient in concrete.

The IDEP is shown in Figure 1. Its dimen-

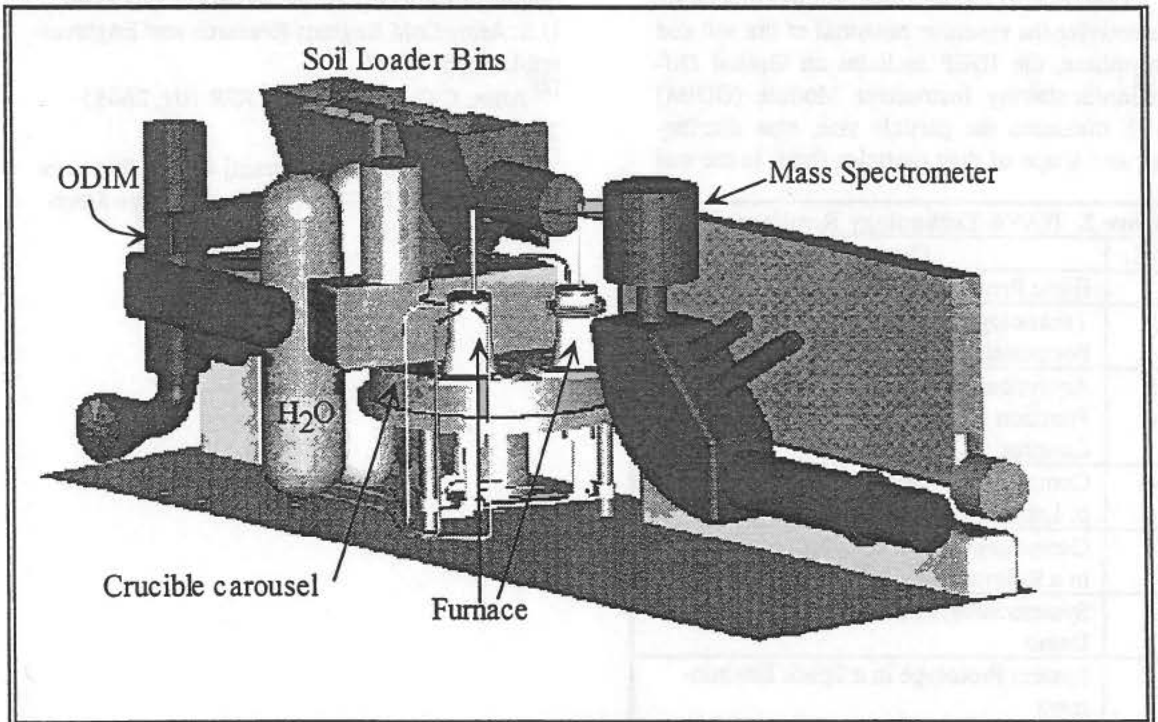

Figure 1. The Integrated Dust/Soil Experiment Package (IDEP) can detect and quantify the abundances of useful materials in the martian soil and atmosphere. ODIM = Optical Diffraction Instrument Module. See text for discussion.

sions are 15 cm x 15 cm x 45 cm, and its mass is 7.74 kg. Chemical reactivities of soil and dust are measured using high- and low-temperature furnaces, a mass spectrometer, and micro-electrodes.

The high-temperature furnace heats samples to as high as 900°C and their evolved gases are quantified by the mass spectrometer. Samples can be exposed to water vapor or hydrogen, and their reaction products measured. In the low-temperature furnace, samples are exposed to water so that their oxidation potential, pH, and electrical conductivity can be measured by miniature solid-state sensors. Trace elements such as Cl and F that are released from the soil by heating can also be measured.

When the mass spectrometer is not being used to measure evolved gases from the soil, it can be opened to the atmosphere (with an in-line dust filter) to conduct long-term monitoring of atmospheric constituents. Bulk atmospheric composition can be measured to an accuracy of 1% to the 3 ppm level, and 20% to the 20 ppb level. Isotopic ratios of C, O and N can be determined to an accuracy of 0.1% by summing 100 scans of the spectrum. This exceeds the accuracy of the Viking instrument by at least an order of magnitude.

In addition to the instruments used to directly characterize the resource potential of the soil and atmosphere, the IDEP includes an Optical Diffraction/Scattering Instrument Module (ODIM) which measures the particle size, size distribution, and shape of dust particles (both in the soil and in the atmosphere). It also measures the total dust density of the atmosphere at the landing site.

The instrument package also includes the Electrostatic Properties Experiment (ESPE) which determines the degree to which soil dust and airborne dust adhere to various surfaces, and it provides information on how to clean those surfaces. Finally, the mechanical system that is used to manipulate soil samples can also be used to expose enzymes or other biomass to the martian soil to determine soil genotoxicity.

The package consists of five major instruments, with relatively high to very high technology readiness levels (see Figure 2). Its heritage includes the research done for the Regolith Evolved Gas Analyzer (REGA)[3]. Moreover, the mass spectrometer has a technology readiness level of 9 (flight-proven system), with previous versions flown in the Apollo and Pioneer Venus missions among many others.

The IDEP can provide a valuable data set for characterization of the resource potential of martian soils. Because it answers engineering, biology and geology questions as well, it is an efficient choice for future Mars missions.

Figure 2. NASA Technology Readiness Levels

TRL	Description
1	Basic Principles Observed and Reported
2	Technology Concept and or Application Formulation
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
4	Component and/or breadboard validation in Laboratory Environment
5	Component and/or breadboard validation in a Relevant Environment
6	System/Subsystem Model or Prototype Demo
7	System Prototype in a Space Environment
8	System "Flight Qualified"
9	Operations, System "Flight Proven"

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[2] Allen, C.C. *et al.* (1996), *JGR 101*, 26085-26095.
[3] Allen, C.C. (1997) [abstract] *In Situ Resource Utilization (ISRU) Technical Interchange Meeting*, LPI, Houston.

A LiF SILICON SANDWICH COUNTER TO MEASURE WATER CONTENT OF PLANETARY SURFACES*. D. M. Drake[1], Benton C. Clark[2], Bruce M. Jakosky[3], Robert Reedy[4], and Steven W. Squyres[5], [1]Amparo Corporation, Santa Fe, NM 87504, [2]Lockheed Martin Astronautics Group, Denver CO 80201, [3]Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309-0392, [4]NIS-2, Los Alamos National Laboratory, Los Alamos, NM 87545, [5]Laboratory for Planetary Studies, Space Sciences Building, Cornell University, Ithaca, NY 14853-6802.

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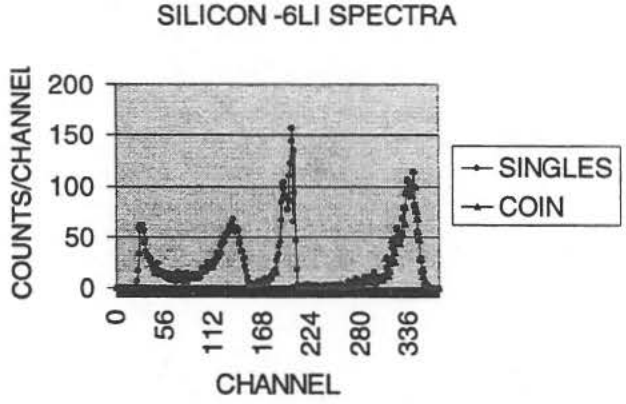
Neutron spectra provide a sensitive tool that can be used to detect the presence of hydrogen, presumably in the form of water, in planetary surfaces. Neutrons are produced by the interaction of cosmic rays with the nuclei that compose the upper several kg/cm^2 of surface material. The neutrons are initially produced by these interactions with energies above 1 MeV but through scattering from surrounding nuclei lose energy and form a spectrum of lower energy neutrons that is generally divided into two parts with the dividing energy near 0.1 eV. The portion of the spectrum above this energy is called epithermal and is operationally defined as neutrons that lose energy in each collision. Below this energy, the neutrons can either gain or lose energy depending upon the thermal motion of the surrounding nuclei.

Scattering by hydrogen is by for the most effective way for neutrons to lose energy and progress from the epithermal to the thermal portion of the spectrum. The presence of hydrogen therefore feeds neutrons into the thermal part of the spectrum at the expense of epithermal neutrons. A change of water concentration from 1% to 2% decreases the epithermal amplitude by about 50%.

The neutron counter proposed here has a long history and was commercially available in a somewhat different form. This counter would be suitable for a rover or lander since it requires a rather long measuring time for each placement. It consists of two silicon wafer charged-particle counters with a layer of ^{6}LiF deposited on the inner surface of one. The neutron detecting reaction is ^{6}Li(n,^{3}H)^{4}He in which the alpha particle and the triton are emitted from the ^{6}Li deposit back to back. If one of the detectors sees the alpha particle, the other will see the triton. This allows one to use a coincidence technique that virtually eliminates all background. The signals from each detector can be added together so that the total energy of the reaction, Q=4.6 MeV and the kinetic energy of the neutron, can be recorded. The accompanying figure shows two spectra of such a counter. One spectrum (singles) shows the pulse height spectrum of one of the silicon wafers. This is overlaid by the coincidence spectrum in which the signals from the alpha particle and the triton are added together. The detector thus can measure the spectrum of high-energy neutrons as well as those in the epithermal and thermal range. To separate the thermal and epithermal counting rates (both of which would be recorded in the peak) two counters would be used, one enclosed by a thin layer of cadmium, and the second by a similar layer of tin. The cadmium layer effectively absorbs all neutrons below 0.4 eV. The tin layer has essentially the same scattering cross section as the cadmium above 0.4 eV and thus compensates for its absorption and scattering. The fast neutron spectrum is also recorded above the ^{7}Li-breakup peak.

Due to the coincidence nature of the counters, an event in one of the wafers that has no corresponding event in its counterpart will not be recorded in the spectra. Counts due to the high-energy cosmic-ray protons could give coincidence events but their pulse heights would by much lower than the ^{6}Li reaction with its high Q value.

The ^{6}Li deposit has to be thin (approximately 150 micrograms/cm^2) so the alpha particle and the triton energies can be recorded with little energy loss. The lithium reaction cross section is smaller than that of ^{3}He, a gas that is frequently used in proportional counters for neutron detection. These two facts make the efficiency of this counter rather small. For example, the efficiency per centimeter squared of this system is about 150 times smaller that that of the ^{3}He counters. We have estimated the neutron flux produced by a typical cosmic-ray spectrum on a lunar type surface and folded it with the efficiency of a sandwich counter. The estimated counting rate for a 2000 mm^2 area wafer near completely dry soil is about 200 counts/hour for the tin covered counter and 120 counts/hour for the cadmium one. The detector is lightweight, and requires little power. Cloning counters can easily increase the counting rate.



GAS GENERATION AND CRYOGENIC REFRIGERATION TECHNOLOGIES. J.E. Fenner[1] and K.A. Edman[2], [1]Armstrong Laboratory, USAF, 2504 Gillingham Drive Suite 25, Brooks AFB, TX 78235-5104, jfenner@alcft.brooks.af.mil, [2]Armstrong Laboratory, USAF, 2504 Gillingham Drive Suite 25, Brooks AFB, TX 78235-5104, kedman@alcft.brooks.af.mil.

Armstrong Laboratory's Oxygen Systems Team is the USAF focal point and center of expertise for oxygen generation technologies research. The main areas of research are pressure swing adsorption systems, miniaturized cryogenic systems, ion-conducting ceramics, polymers membranes, and miniaturized distillation technology.

Armstrong Laboratory is currently developing the Advanced Hybrid Oxygen System, AHOS. These hybrid systems will liquefy, gaseous oxygen that is generated by a High Performance Molecular Sieve Oxygen Generating System (HP MSOGS), a pressure swing adsorption technology. The HP MSOGS is capable of generating oxygen in concentrations greater than or equal to 99.0%, with peak concentrations at 99.7% oxygen. This capability meets the 99.0% level required by the U.S. Pharmacopoeia (USP) for medical grade "oxygen," and satisfies paratroopers prebreathing concentration requirements. This technology is targeted for heavy aircraft applications (AHOS-Aircraft) and aeromedical evacuation and field casualty care operations (AHOS-Medical). Critical technology developments include: miniaturized, high speed, gas-bearing turbomachinery; high effectiveness heat exchangers; and high purity oxygen concentrators. AHOS will allow the USAF to replace existing non-generation systems in both aircraft and medical applications significantly reducing the cost and logistical burden associated with these systems.

Even though these pressure swing adsorption systems provide many benefits over the existing USAF oxygen infrastructure (bottle gaseous and liquid oxygen), the technology has limitations. Because of these limitations, Armstrong Laboratory is performing extensive research in ion-conducting ceramics, both in-house and through contracts with industry and universities. An oxygen generation system based on ceramic technology does not require a compressed air source; these systems have been able to generate pressurized oxygen when a voltage is applied across the ceramic material at ambient pressures. Pressure swing adsorption oxygen generation systems do require a compressed air source. In most cases on aircraft, this requires an expensive aircraft modification in order to provide the pressurized engine bleed air to the system. Additionally, the quality of aircraft engine bleed air and the contaminants in this air are the primary source of current oxygen generation system failures. For ground medical oxygen generation systems, air compressors must be incorporated on the inlet side of the oxygen concentrator, driving up system weight and tremendously increasing system power consumption. Ceramic-based systems can also be made with relatively few moving parts (in comparison to pressure swing adsorption systems) and, therefore, theoretically have high mean time between failures. However, ceramic/electrode/seal materials still require significant development in order to make this type of oxygen generation system practical.

In addition to AHOS and ceramic materials research, Armstrong Laboratory explores other areas of generation research including polymers/membranes, and invests in technologies such as miniaturized distillation components. The USAF has a large need for self-generating/storing oxygen systems, and is performing extensive research to ensure that technology advances to make these systems viable. Although the atmosphere of application of these technologies varies from NASA's application, the basis of the technology developments and the technology goals run parallel.

IN-SITU GENERATION OF CARRIER GASES FOR SCIENTIFIC ANALYSES ON MARS. J. E. Finn[1] and K. R. Sridhar[2]. [1]Regenerative Life Support Branch, NASA Ames Research Center, M/S 239-15, Moffett Field CA 94035, USA. (jfinn@mail.arc.nasa.gov). [2]Aerospace and Mechanical Engineering, University of Arizona, Tucson AZ 85721, USA (sridhar@shakti.ame.arizona.edu).

The search for useful raw materials on planetary surfaces will involve various scientific analyses of soil and rock samples. The devices performing these measurements often require inert carrier gases for moving analytes and purging instrumentation. At present, the carrier or sweep gas must be carried from Earth in a compressed gas cylinder, and so the supply of this depletable resource sets a hard limit on the life span of the experiment. If a suitable carrier gas could be produced in-situ, then the scientific return of exploration missions could be extended and enhanced greatly. Many more samples could be analyzed, long-ranging rovers could have independent gas supplies, and instrument designs could have added flexibility with respect to gas consumption.

The atmosphere of Mars contains small amounts of nitrogen and argon, a purified mixture of which would form a suitable carrier gas for many kinds of experiments. We are developing a simple device (MICAGG, Mars In-situ Carrier Gas Generator [1]) for extracting and compressing this N_2-Ar mixture on the Martian surface. In addition to being a low-mass, low-volume, and virtually solid state unit, it consumes little or no electrical power. Energy to perform work is taken from the Martian environment using the daily temperature cycle, so the device should operate easily within the strict power limits of *Discovery*-class or *Surveyor* robotic missions. The device would eliminate the need to carry a large gas supply and would remove any significant requirement on valve leakage, as the gas only needs to be preseved for a period of days between experiments. The fabrication of a prototype has been funded by NASA's Planetary Instrument Definition and Development Program under NRA 96-OSS-11.

Both separation and compression aspects of the device are based on principles of pressure- and temperature-swing adsorption, using the diurnal cycle to drive the heat engine. A schematic of the device is shown in Figure 1.

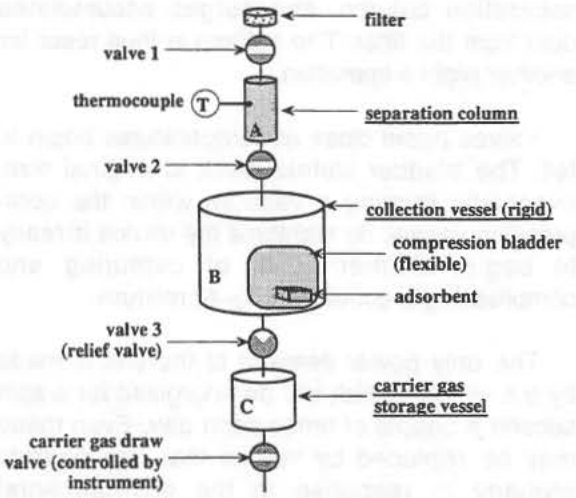


Figure 1. Schematic of a Mars in-situ carrier gas generator.

The device consists of three main components that are separated by valves: a gas separation column, a collection/compression vessel, and a storage vessel. The device operates as follows.

During the cold night, nitrogen and argon are separated from the mostly CO_2 atmosphere in the gas separation column, and flow into the evacuated collection vessel. The column is sized so that the collection vessel is filled (and therefore the flow stops) before CO_2 saturates and breaks through the column. As day approaches and temperatures begin to rise, valves close to isolate the column.

As the temperature continues to rise, a flexible bladder contained within the collection/compression vessel expands and compresses the N_2-Ar mixture. The expansion of the bladder is produced by a specially selected adsorbent/adsorptive pair that has appropriate characteristics for performing the expansion over the desired temperature range. When the N_2-Ar mixture is compressed to a threshold level, it opens a relief valve and flows into the storage vessel. The bladder continues to

expand until the compression vessel is emptied of gas.

Also at the relatively high daytime temperatures, the MICAGG's inlet valve opens to release compressed CO_2 that desorbs from the gas separation column, and purges accumulated dust from the filter. The column is thus reset for another night's operation.

Valves again close as temperatures begin to fall. The bladder shrinks back to original size, eventually forming a vacuum within the compression vessel. By nighttime the device is ready to begin another cycle of capturing and compressing a quantity of N_2-Ar mixture.

The only power demand of the unit is made by the valves, which will be energized for a split second a couple of times each day. Even these may be replaced by valves that can operate properly in response to the environmental temperature changes. For example, "wax motor" actuators have been developed that will operate within the overall Mars temperature regime.

An estimate of the size of a flight-type unit can be made through consideration of the requirements of an existing instrument. The Thermal and Evolved Gas Analyzer (TEGA) that will be carried as part of the Mars Volatiles and Climate Surveyor payload on the *Mars Surveyor Lander 98* uses about 50 standard mL of carrier gas each seven-day period. Using baseline adsorbents, a 70 K temperature swing (as is seen at the *Mars Pathfinder/Sagan Station* site), and an atmospheric pressure of about 5 torr, a unit that would supply the required carrier gases might look similar to the scale drawing shown in Figure 2.

The total MICAGG volume envelope for this particular application would be about 1.5 L and would weigh a little more than 90 g. We estimate that the alternative, a pressurized gas cylinder carrying a full supply for a two-year mission, would occupy an envelope of at least 6.9 L and weigh at least 200 g.

A MICAGG could be used on any future lander or rover mission to Mars that requires a carrier or sweep gas. Its principles of operation can be applied on other planetary bodies possessing atmospheres. It should also be noted that device also provides a technology demonstration for compression of Mars atmospheric carbon dioxide using the diurnal temperature cycle, as well as buffer gas production for life support on future human missions to Mars.

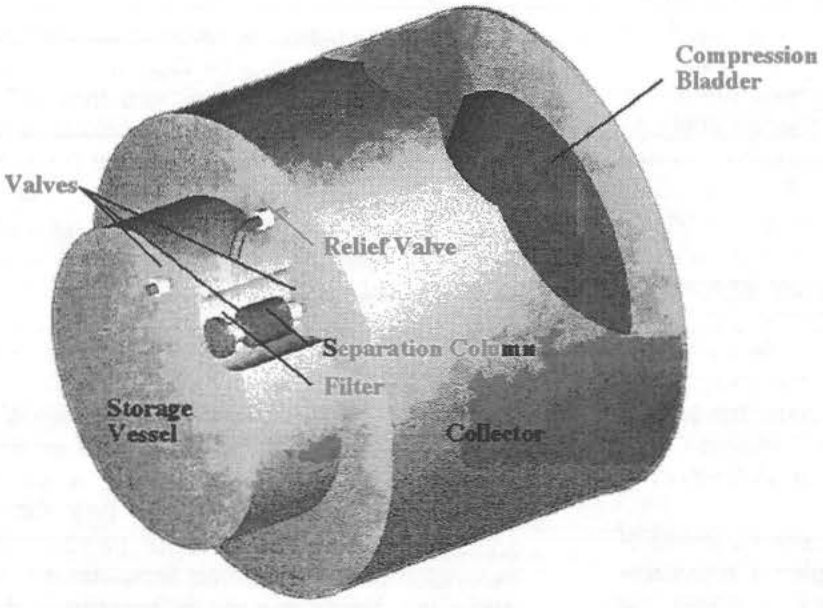


Figure 2.
An approximately 1/3-scale drawing of the MICAGG concept for the application discussed in the text. The cutaway reveals the compression bladder contained with the collection/ compression vessel.

[1] Finn, J. E. and Sridhar, K. R., "Mars in-situ carrier gas generator," Paper No. 972497, 27th International Conference on Environmental Systems, Lake Tahoe, Nevada, July 14-17, 1997.

MINIATURIZED MATERIAL SAMPLING AND TRANSFER DEVICES FOR EXTRATERRESTRIAL EXPLORATION. S. Gorevan, S. Rafeek, T. Myrick, K.Y. Kong, and P. Mahaffey., Honeybee Robotics, Ltd., 204 Elizabeth Street, New York, NY 10012, gorevan@hbrobotics.com, rafeek@hbrobotics.com.

For early extraterrestrial exploration with a limited payload, miniaturize sampling devices that can be mounted on a rover platform will be crucial in locating areas with high resource concentration for future extraction, storage and utilization. Two such rover friendly sampling devices are the gas Sniffer and the Sample Acquisition and Transfer Mechanism (SATM). The Sniffer is a miniaturize gas sampler that can be utilized for the characterization of atmospheric, surface and subsurface molecular composition as a function of time and site location. The device is embodied in the tip of a non-rotating drill sleeve just behind the auger and cutting head (see Figure 1).

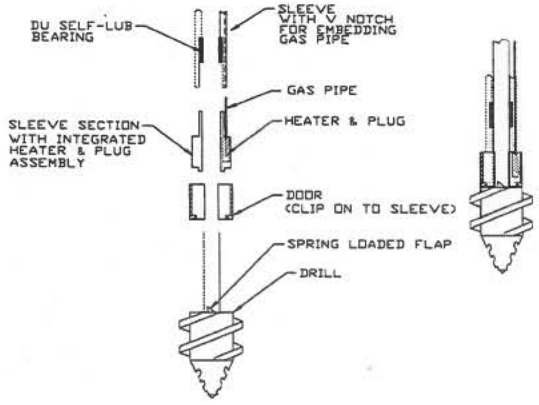


Figure 1: Components of the Sniffer.

It consists of a porous gas permeable ceramic plug in which is embedded a heating element and to which is attached a flexible capillary tube (embedded in the drill stem) which is continuously evacuated by a pump on the mass spectrometer (mounted on the rover). The ceramic plug and heating element is protected from surface dust and also during subsurface drilling by a retractable cover which also scoops adjacent solid phase material towards the heating element. For atmospheric samples, the dust cover is retracted and atmospheric gas is pumped into the spectrometer. Similarly surface and subsurface samples can be acquired by moving the drill to the

selected surface site or drilling to the required depth and retracting the protective cover to bring solid phase samples in contact with the heater (see Figure 2). Upon heating, a portion of the evolved gas

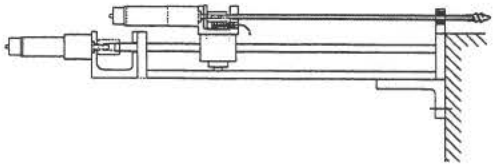


Figure 2: Miniature drill with gas Sniffer

will permeate the ceramic plug and get sucked up into the mass spectrometer for analyses.

SATM is another highly developed miniature sampling device that can repeatable deliver solid phase samples (acquired from the surface to depths of 1 meter below surface) to a number of on-board instruments such as microscopes (for cataloging), ovens (for composition analyses) and/or to a hermetically sealed sample return canister for a sample return mission (see Figure 3).

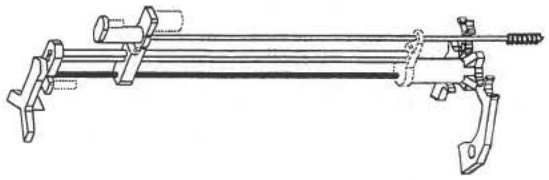


Figure 3: SATM drilling hardware (1m stroke)

A double auger drill tip design allows the SATM to acquire and seal samples at depth before transferring them to the surface for analyses.

This miniaturization approach to extraterrestrial exploration makes efficient use of limited rover mass and power resources while providing invaluable geochemical and even exobiological information for future large scale resource utilization.

INTERMEDIATE-TEMPERATURE ELECTROLYSIS CELLS FOR OXYGEN PRODUCTION FROM CARBON DIOXIDE. H. Hu and T. Yadav, Nanomaterials Research Corporation, 2849 East Elvira Road, Tucson, AZ 85706, USA (hhu@nrcorp.com).

Among techniques proposed for producing oxygen from carbon dioxide on Mars, oxygen generators based on solid-oxide electrolysis cells have the advantage of simplicity in construction and operation. With such cells, oxygen is generated by decomposition of carbon dioxide under applied electric current. This is a reverse process to fuel cell operation, in which electricity is generated by oxidation of fuels with the consuming of oxygen. Therefore, knowledge gained from solid oxide fuel cell (SOFC) studies can be lent to the development of solid-oxide electrolysis cells for oxygen production from carbon dioxide.

The current SOFC technology is based on stabilized zirconia electrolytes. Most of current SOFCs are operated at about 1000 °C or higher, mainly because the voltage loss of the cell is significant below 1000 °C. In particular, polarization overpotentials at the electrolyte-electrode interfaces account for the major part of the voltage loss at lower temperatures. High operating temperature not only causes problems related to power efficiency, but also causes many other problems including undesirable reactions between cell components and materials degradation during cell fabrication and operation, leading to questions in durability and reliability. Many of the difficulties can be alleviated if the cells can be operated at intermediate temperatures. Significant efforts have been devoted to developing solid oxide electrolytic cells that can be operated at intermediate temperatures (600-800 °C). To NASA planetary expeditions, lower operating temperature and power consuming also means lighter weight, and thus is of additional significance.

In this project, Nanomaterials Research Corporation has sought to develop intermediate-temperature electrolysis cells based on YSZ electrolyte. The work has been focused on nano-engineering of the electrolyte-electrode interfaces in order to minimize interfacial overpotentials and total cell resistance at intermediate temperatures. A series of mixed ionic-electronic conducting (MIEC) metal-ceramic nanocomposites have been studied as electrode materials for YSZ-based electrolysis cells. Impedance spectroscopy and dc measurement have been used for identifying highly catalytically active MIEC nanocomposite electrode materials under oxygen pump conditions.

It has been observed that the nanocomposite MIEC electrodes can significantly reduce the interfacial resistance of the cell as compared with pure precious metal (Pt or Ag) electrodes. In oxygen-rich atmosphere, Ag-containing electrodes show much smaller interfacial resistances than Pt-containing electrodes. DC measurements also indicated that Ag-containing electrodes show lower interfacial overpotentials when used on the oxygen side. Overall, Ag-containing MIEC materials appear to be good candidates for the electrode on the oxygen side. On the CO_2 side, especially under dc bias, Pt-containing electrodes seemed to perform better than Ag-containing electrodes. Compared to conventional YSZ-based cells, cells with new MIEC nanocomposite materials showed a significant increase in oxygen generation efficiency. In summary, MIEC nanocomposites offer a great potential of making intermediate-temperature YSZ-based electrolysis cells for oxygen generation while sustaining high efficiency.

MICROTEL: A TV MICROSCOPE FOR PLANETARY FIELD GEOLOGY AND RESOURCE EVALUATION. Petr JAKEŠ, Institute of Geochemistry, Mineralogy and Mineral Resources, Charles University, Albertov 6, Praha 2, 128 43 Czech Republic, phone: +42 2 21952426, fax:+42 2 296084 e-mail: jakes@prfdec.natur.cuni.cz

In order to exploit mineral resource the useful component must be identified, characterised and (its) reserves calculated. Exploration involves consecutive steps of increasing knowledge of geological and technological data that lead from identification of a potential resource to calculation of "proven" reserves. This includes mineral identification, determination of proportions and relationships between the usable and unusable part of the resource, as well as the examination of features (e.g., morphology of particles, mineral intergrowths) that may influence the technology needed to extract the useful component. On the Earth the task is perfomed by trained geologists, and the additional data are obtained in laboratories. Geologist is trained to use hand held lens in order to examine minerals of rocks since grain size is usually smaller than the resolution of naked eye. The use of microscope in laboratory technological essays is of prime importance.

Strategies for the exploration for planetary resources exploration may differ, though the principal aspects i.e., identification of rocks and their mineral particles, morphologies, textures, will be part of the resource charting (tonnage estimation) and evaluation of its quality (ore grade) which relates to technological process, energy requirements etc.

Extraterrestrial rocks (lunar rocks and soils, meteorites - asteroids) and images of planetary surfaces (e.g., Mars or Venus) suggest that grain size of rocks to be explored are similar to terrestrial ones. Field geology, petrology and geochemistry will constitute major exploration efforts and will require data on the shape, composition, size and arrangement of rock soil/ore particles. In geology-petrology-geochemistry oriented missions, whether human or robotic, the visual (image) analyses will play leading role in decision making. Chemical data, rock textures, particle sizes and shapes (optical image analysis) should be used to select sites particularly the combination of chemical compositions and morphological data.

When imaging and area of relatively small size (e.g., 5 x 5 millimeters) in order to estimate modal volume proportions of phases which appears as areas of the same optical properties with submillimeter size one needs a small, light-weight optical image system with possibility to calibrate magnification, and to control light wavelengths. The instrument must produce colour images and must have identification capabilities. The design must be rugged, with easy manipulation of data and low power consumption.

To obtain "mineralogical and morphologic" information "in situ" on planetary surfaces we have designed, constructed and undertaken preliminary tests of a

Mikrotel, compact TV - microscope imaging system that allows us to image an area of several square centimeters and/or millimeters of planetary surface (regolith or rock samples) (Jakes, 1992). The Microtel has been constructed with minimum of moving parts. Because of its simplicity it could be part of a robotic probe or could be used by an astronaut as a hand -held lens. The microscope (or hand held lens equivalent) uses a photosensitive device (e.g., CCD chip) combined with the microscopic lenses, mirrors, internal light and/or fiber optics to image the area in visible, UV or NIR. The size of the monitored area translated to magnification could be easily changed, depending on needs, by varying the optics . The other modes of magnification, i.e., false electronic magnification, through dense CCD chips could be used as well. Microscope lenses with a short working distance between the optic system and the "eye" (CCD) are used. Magnification of 10 to 1000 times (using a TV screen) were explored. The best results were obtained with magnifications of 10 times to about 100 times at the TV screen provide good images with sufficient depth of focus and good resolution (better than 5 microns). Different appeatures are used to vary the depth of the focus. The device is connected by cable to a signal processing unit and to TV monitor, videoprinter, videorecorder or PC. The equipment camera and illumination with focusing system is small and light-weight (50 x 50 x 20 millimeters, or tube of 100 mm long and 20 mm in diameter) and less than 250g. The Mikrotel has its own light source and is easily transportable, allowing the imaging of normally inaccessible areas.

Internal light source illumination makes the examination independent of external conditions, and light wavelengths could be easily calibrated. If a tuneable source (Chrien et a., 1994) were used, multispectral images using monochromatic light could be produced. Computer combination of images taken at different defined wavelengths can provide a color images. UV illumination providing the "visible light" effects could be added to detect "fluorescent phases" (e.g., quartz, zircon, etc). The use of the discrete light wavelengths (including NIR,IR), computer processing of the images, and the processing the images makes the Mikrotel into a powerfull identification tool.

The optical determination of mineral phases (rock consituents) usually preceeds more sophisticated determinations of chemical compositions. It is imperative for exploration geology that analyzed areas are imaged, at least in a visible light spectrum. Therefore the imaging system has been designed for the science package of Nanokhod (Rieder et al., 1995) which contains alpha proton, XRF and Moessbauer spectrometries and a Microtel imaging system. The microscope is built to image the area of the chemical analyses i.e., approximately 40 x 40 millimeters, as well as an area of greater detail (approximately 4 x 4 millimeters) with a resolution better than 10 μm. Fixed focus optics connected to two chips, and different colour illuminations (470, 565, and 635 nm) are used. Electronics integration for this camera is being built in DLR Berlin (Harald Michaelis group).The size of the camera with two magnifications is 70 x 40 x 30 milimeters, and weight does not exceeds 150 g.

Resource evaluation requires, however, requires that a third dimension e.g., depth is explored and we have experimented with soft penetrator microscope-stratigraphy tool. The stratigraphy in the regolith that covers planetary surface provides a direct record of planetary evolution and could be important to volume estimations of a resource. The use of a microscope, hand-held imaging system in the drilling will enable the soil profile - mineral composition to be studied as a function of the depth. Although the usefulness of such tool for resource estimation (e.g., amount of ilmenite in the surface layer of lunar regolith) is unquestionable, the method needs further development.

We see the future of optical imaging not only in an exploration phase but also as a mode of control of future technological processes. We also see the need to carry out research in TV microscope reflectance spectroscopy.

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ENGINEERING PROPERTIES OF THE REGOLITH ON THE MOON AND MARS RELATED TO ISRU

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Introduction: In Situ Resource Utilization on the Moon and Mars requires devices that detect and quantify the abundance of useful raw materials. We also need machines that process the raw materials into useful resources. Knowledge of the mechanical properties of lunar and Mars regolith is essential to success in designing both the devices and machines.

Regolith: Regolith is the loose material overlying more intact strata on the Moon and Mars. It varies in thickness from several meters on the maria or lunar seas to many meters on the highlands of the Moon. The regolith is the material humans walked and drove on in 1969 through 1972. In the future, people will use it for radiation protection and as a resource for recovery of oxygen, silicon, iron, aluminum, and titanium. Implanted in the lunar regolith by the solar wind are recoverable amounts of volatiles such as hydrogen and helium. Currently our knowledge of the mechanical properties of surface layers on the Moon and Mars is rudimentary. Establishment of pilot plants to demonstrate in situ resource recovery, and eventually mining, manufacturing, and habitat construction on the Moon and Mars requires a systematic effort to fill gaps in our knowledge of the mechanical properties of surface layers on the Moon and Mars. In the late 60s and early 70s, two Viking Landers operated on Mars, with a surface sampler device. The Viking Landers operations provided insight into the mechanical properties of the Mars surface layers. Pathfinder, with Sojourner Rover, is currently gathering more data, to be analyzed, regarding the properties of surface material on Mars. There is much more to be learned about the mechanical properties of surface layer on both the Moon and Mars.

Required Technologies: The tasks of detecting, quantifying, and then processing raw materials into useful resources, on Mars and the Moon, require knowledge of the engineering properties of surface materials of the Moon and Mars. Terrestrial experience, and the established technologies of geotechnical engineering and mining engineering, on Earth, can serve only as a point of departure in understanding behavior of surface materials on the Moon and Mars. Differing operational constraints, environments (e.g., gravity and atmospheric pressure), and the variety of regolith-forming processes on the Moon, Mars, and Earth severely limit the usefulness of extrapolation of terrestrial soil and rock handling and processing experience to the Moon and Mars. On Earth we use large and heavy excavation and soil and rock processing equipment that is not practicable on the Moon and Mars.

Experience with Project Apollo roving vehicles, bootprints, core tubes, trenching, ALSEP, etc. is useful in planning the Mars surface operations and analyses. Raw materials of the Moon and Mars include: rock, soil, moisture, gas in voids, and atmospheric components (outside of scope of this paper). We need to know the physical attributes such as particle size distribution, relative density, and consistency (stiffness). We need to know how to test soils and rock on the Moon and Mars that will most efficiently yield engineering data most useful in ISRU. Needed are quick and simple tests and techniques of sampling. For mining and construction operations there are requirements for information on bulk densities, swell factors, diggability, rippability, drillability, and blast response. Definitions and appropriate measures of these parameters are required for the one-sixth g and 0.38 g environments of the Moon and Mars. There is a need to determine the most efficient methods of mining for the Moon and Mars. Examples of sources of information on the mechanical properties of Mars surface layers include [1]. They stated "Analyses of sample trenches excavated on Mars, using a theory for plowing by narrow blades, provide estimates of angle of internal friction and the cohesions of Martian surface materials. Angles of internal friction appear to be the same as those of many terrestrial soils, because they are generally between 27° and 39°. Drift material, at the Lander 1 site, has a low angle of internal friction (near 18 degrees). All of the materials excavated have low cohesions, generally between 0.2 and 10 kPa. The occurrence of cross bedding, layers of crust, and blocky slabs shows that these materials are heterogeneous and that they contain planes of weakness. The results reported here have significant implications for futures landed missions, Martian eolian processes, and interpretations of infrared temperatures." One useful approach to gathering data on lunar soils was use of core tubes and drill cores. The Apollo core tubes [2] evolved over the course of the Apollo program. The Apollo 15-17 core tubes were thin-walled (.26 cm), of larger diameter (4.13 cm internal diameter), and created much less sample disturbance than did the Apollo 11, 12, and

14 core tubes (1.97 cm internal diameter and 3.32 cm external diameter). The Apollo 11 bit had an inward flare leading to severe sample distortion. Apollo 12-14 bits were more conventional so that the samples were not required to constrict to enter the tube. Still, the tube was thick-walled and significant sample disturbance was produced. Apollo 15-17 tubes were thin-walled with an area ratio of 14% compared to 140% for Apollo 12-14 tubes. 21 core tubes were driven into the regolith, pulled out, and then returned to Earth by Apollo astronauts for study. Ten were single length and 11 were double length. Depths of regolith sampled ranged from 10 cm on Apollo 11 to 298.6 cm on Apollo 17.

Gaps in Knowledge: We have gaps in our knowledge [3, 4]. First, the areas sampled are a very small part of the lunar surface. Even in the areas sampled, additional data is needed, both in situ and on recovered lunar samples. The stress-strain relationships at low stresses are not well known at the locations visited. Some soil particles, e.g. agglutinate particles and even breccias, may break up as load is increased and repeated. Behavior under repeated loading has not been determined.

Dust mitigation is very challenging in the lunar and Mars environments and poorly understood. There will be operations-induced transport of dust [5]. Apparently, on the Moon, there are natural dust levitation mechanisms associated with charge differences built up by photo-conductivity effects near the day-night terminator.

We need to better understand soil variability both horizontally and vertically. Some sites, such as the Apollo 16 site show much variability. At the Apollo 16 site, results of penetration tests, analyses of footprint and LRV track depths, and core tube sample data were used to deduce vertical and lateral variability in soil properties. There are significant variations vertically and horizontally in soil properties that probably reflect individual cratering and depositional events. The conclusion is that although lunar surface appearance may be suggestive of relative uniformity, variability in soil physical properties may be great. Penetration tests and study of core samples will readily detect variations in near-surface soil stratigraphy. Bedrock and boulders in the subsurface complicate planning for some operations. How deep is bedrock and in what condition? Energy requirements for excavation, backfilling, and deep drilling are unknown. We need methods to efficiently map subsurface boulders and variations in strata.

Carrier, Mitchell, Leonovich, et al. [2] suggest that a curved Mohr Coulomb equation would better describe the lunar soil shear strength. The values of shear strength parameters ϕ and c available for the Moon may be adequate to use in design for near-surface construction. When deep excavations and heavy-loaded structures are designed it will be essential to better understand the shear strength of lunar soil under high stress conditions.

Recommendations: We suggest that each future visit by robots and humans to the Moon and Mars be used as an opportunity to gather required data on the regolith mechanical properties and behavior at all locations visited. An active program is needed to analyze the data and do comparisons and correlations of what is learned in this data-gathering effort. One product of this effort will be validated terrestrial simulants of Mars surface materials and enhancements of current lunar soil simulants. Validated simulated Mars and lunar soils are required to do meaningful pre-flight testing on Earth of ISRU soil-handling equipment intended for use on the Moon and Mars.

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OXYGEN EXTRACTION USING A CERAMIC HONEYCOMB TECHNOLOGY

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The results of a NASA-supported study are reported to examine if a ceramic-honeycomb technology can contribute to producing oxygen from the Martian atmosphere. The honeycomb technology is based on a stabilized Bi_2O_3 ceramic composition and has been developed for extracting oxygen from air in the 500-600 °C range.

Single-wall honeycomb plates with electroded channels were measured 550-700 °C in air ($2x10^5$ ppm O_2), CO_2 (20 ppm), and N_2 (0.5 ppm). Channel resistances were measured as a function of oxygen-ionic current densities up to 0.5 A/cm^2, and the power densities are approximately the same in all three gases for current densities above 0.1 A/cm^2, as shown in Fig. 1. These results are attributed to the extraction of oxygen from the gases rather than to the dissociation of CO_2, and free-energy calculations support this interpretation. It is concluded that this honeycomb technology can extract the residual oxygen (1500 ppm) directly from the Martian atmosphere at relatively low temperatures (550 °C). At 0.5 A/cm^2, about 30 cm^3 of ceramic honeycomb would extract 1 kg of oxygen per day.

The best oxygen-extraction results in this study were obtained with a ceramic electrode and a silver overlay on the honeycomb channels. Finally, free-energy calculations show that the Bi_2O_3-based ceramic is stable against reduction in the Martian atmosphere, and this supports the experimental observations in CO_2 and N_2.

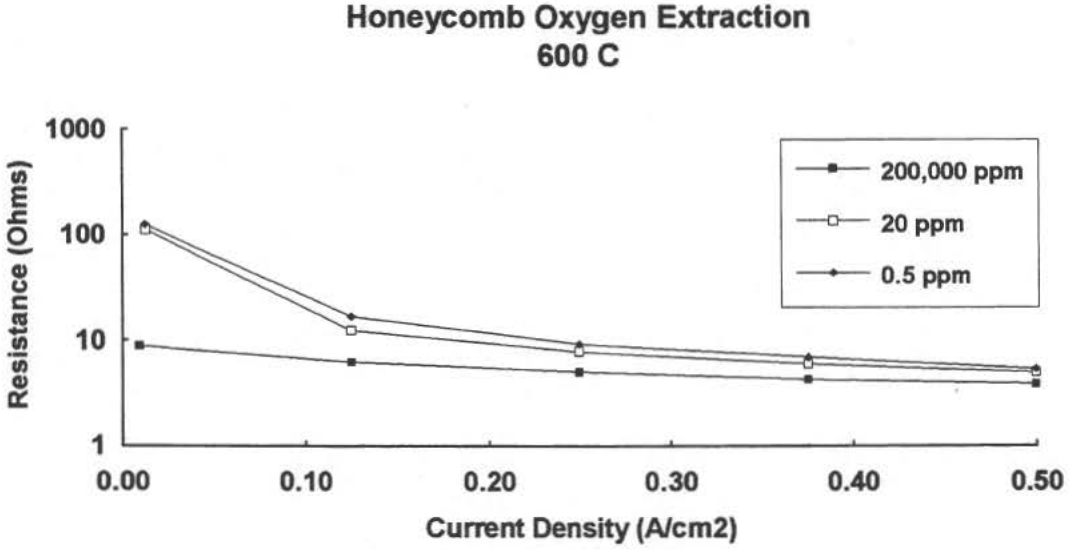


FIGURE 1. Measured honeycomb-channel resistance at 600 °C as a function of oxygen-ionic current density in air ($2x10^5$ ppm O_2), CO_2 (20 ppm), and N_2 (0.5 ppm). Ionic currents are due to the extraction of oxygen from these gases.

Oxygen Liquefaction and Zero-Loss Storage System

F. N. Lin, T. R. Bollo, and D. M. Peterson
Materials Science Lab, Kennedy Space Center

Extended Abstract

This paper presents an alternative concept that employs existing technologies and off-the-shelf components to liquefy gaseous oxygen from an in-situ propellant production (ISPP) unit and to store the liquid oxygen without boil-off loss. A primary goal is to minimize active components with a secondary goal of designing the active component in a protected or failure-free environment. The resulting design requires only one active component, a compressor operating in a closed and consequently more protected system. The design avoids pumps as active components by employing cryopumping for gaseous oxygen (GOX) and gravity transfer for liquid oxygen (LOX). Although there are a variety of possible system configurations, the figure below is a basic example of these concepts.

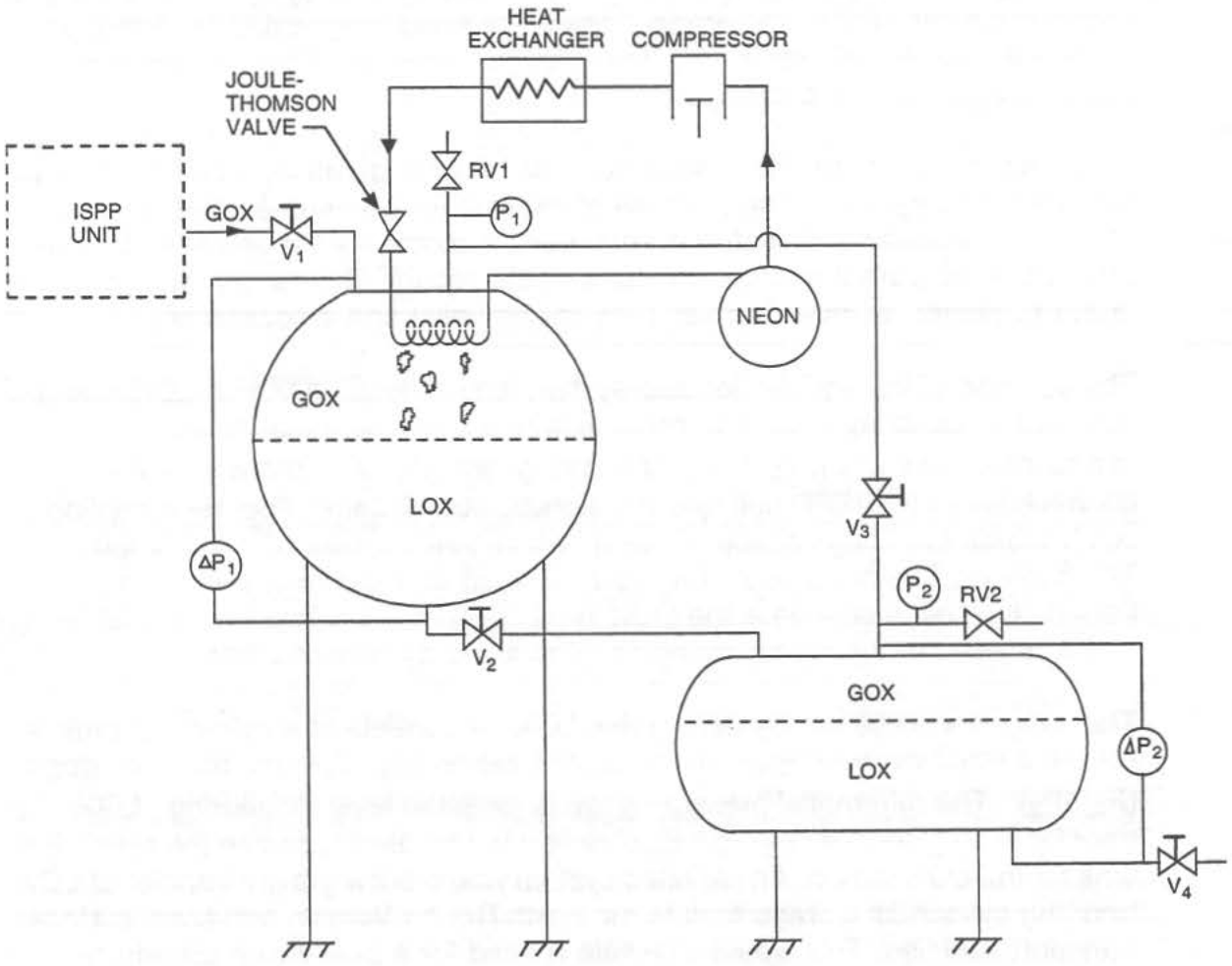
As shown in the figure, the system consists of a refrigeration, a liquefaction and a storage sub-system. The purpose of the refrigeration sub-system is to provide the cooling for liquefaction and boil-off control for the storage. It uses neon as a refrigerant and consists of a bottle/accumulator, a compressor, a heat exchanger, a Joule-Thomson expansion valve and a cooling coil.

The purpose of the liquefaction sub-system is to convert GOX into LOX with a secondary capability of LOX storage. It consists of a spherical tank, control/relief valves(V_1, V_2, RV_1), pressure gages (P_1, ΔP_1) and associated connections to the ISPP unit and the storage sub-system. The neon cooling coil is inside the ullage space of the spherical tank so that, after the Joule-Thomson expansion, a cooled mixture of liquid and gaseous neon passes through the coil to condense the GOX into LOX. The GOX flow from the ISPP unit is a result of the cryopumping effect induced by condensation.

The oxygen storage sub-system stores LOX. It consists of a cylindrical tank, a pressure relief valve (RV_2), two flow control valves (V_3, V_4), and pressure gages (P_2, ΔP_2). The differential pressure gage is for liquid level monitoring. LOX transfer is by gravity so the spherical tank must be always above the cylindrical tank for the LOX to flow. An elevated system would allow gravity transfer of LOX from the cylindrical storage tank to the Earth-Return-Vehicle and Mars surface transport vehicles. This would eliminate a need for a LOX pump anywhere within the system.

Operation of the system is straight forward. Initially, V_1 is open and all other valves are closed. When the pressure in the spherical tank, as indicated by P_1, reaches a pre-set value, the neon sub-system engages. The GOX in the spherical tank will condense into LOX and the pressure P_1 will decrease. The neon sub-system will turn off when the pressure P_1 decreases to a pre-determined value. When the spherical tank is almost full, as indicated by the differential pressure ΔP_1, the LOX will gravity flow to the cylindrical tank by the opening V_2 and V_3. Boil off from the storage subsystem returns to the spherical tank for liquefaction. Thus, we have a zero-loss system.

MARTIAN ATMOSPHERE:
0.1 to 0.15 psia
-24°F to -190°F



OXYGEN LIQUEFACTION AND ZERO-LOSS STORAGE SYSTEM

IN SITU IDENTIFICATION OF MINERAL RESOURCES WITH AN X-RAY-OPTICAL "HAND-LENS" INSTRUMENT

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The recognition of material resources on a planetary surface requires exploration strategies not dissimilar to those employed by early field geologists who searched for ore deposits primarily from surface clues. In order to determine the location of mineral ores or other materials, it will be necessary to characterize host terranes at regional or subregional scales. This requires geographically broad surveys in which statistically significant numbers of samples are rapidly scanned from a roving platform (1).

To enable broad-scale, yet power-conservative planetary-surface exploration, we are developing an instrument that combines x-ray diffractometry (XRD), x-ray fluorescence spectrometry (XRF), and optical capabilities; the instrument can be deployed at the end of a rover's robotic arm, without the need for sample capture or preparation. The instrument provides XRD data for identification of mineral species and lithological types; diffractometry of minerals is conducted by ascertaining the characteristic lattice parameters or "d-spacings" of mineral compounds. D-spacings of 1.4 to 25 angstroms can be determined to include the large molecular structures of hydrated minerals such as clays. The XRF data will identify elements ranging from carbon (Atomic Number = 6) to elements as heavy as barium (Atomic Number = 56).

While a sample is being x-rayed, the instrument simultaneously acquires an optical image of the sample surface at magnifications from 1x to at least 50x (200x being feasible, depending on the sample surface). We believe that imaging the sample is extremely important as corroborative sample-identification data (the need for this capability having been illustrated by the experience of the Pathfinder rover). Very few geologists would rely on instrument data for sample identification without having seen the sample. Visual inspection provides critical recognition data such as texture, crystallinity, granularity, porosity, vesicularity, color, lustre, opacity, and so forth. These data can immediately distinguish sedimentary from igneous rocks, for example, and can thus eliminate geochemical or mineral ambiguities arising, say between arkose and granite. It would be important to know if the clay being analyzed was part of a uniform varve deposit laid down in a quiescent lake, or the matrix of a megabreccia diamictite deposited as a catastrophic impact ejecta blanket.

The unique design of the instrument (2,3), which combines Debye-Scherrer geometry with elements of standard goniometry, negates the need for sample preparation of any kind, and thus negates the need for power-hungry and mechanically-complex sampling systems that would have to chip, crush, sieve, and mount the sample for x-ray analysis. Instead, the instrument is simply rested on the sample surface of interest (like a hand lens); the device can interrogate rough rock surfaces, coarse granular material, or fine rock flour (4). A breadboard version of the instrument has been deployed from the robotic arm of the Marsokhod rover in field trials at NASA Ames, where large vesicular boulders were x-rayed to demonstrate the functionality of the instrument design, and the ability of such a device to comply with constraints imposed by a roving platform (2).

Currently under development is a flight prototype concept of this instrument that will weigh 0.3 kg, using ~4500 J of energy per sample analysis. It requires ~5 min. for XRD analysis, and about 30 min. for XRF interrogation. Its small mass and rugged design make it ideal for deployment on small rovers of the type currently envisaged for the exploration of Mars (e.g., Sojourner-scale platforms). The design utilizes a monolithic P-N junction photodiode pixel array for XRD, a Si PIN photodiode/avalanche photodiode system for XRF, and an endoscopic imaging camera system unobtrusively embedded between the detectors and the x-ray source (the endoscope with its board-mounted camera can be adapted for IR light in addition to visible wavelenths. A rugged, miniature (~7 cm3) x-ray source for the instrument has already been breadboarded (5).

(1) Marshall, J. (1996) LPS XXVII, 809, (2) Marshall, J., et al. (1996) LPS XXVII, 815, (3) Koppel, L, et al. (1995) Proc. 44th Ann. Denver Conf. Applic. X-Ray Analysis, P2-35, (4) Keaten, R., et al. (1995) EOS, Proc. AGU, F334 (P12A-19), (5) Koppel, L. & Marshall, J. (1997) Rev. Sci. Instr. (AIP), submitted.

HYDROGEN TRANSPORT TO MARS ENABLES THE SABATIER/ELECTROLYSIS PROCESS. P. J. Mueller[1] and D. Rapp[2], [1]Space Dynamics Laboratory, Utah State University (1695 Research Park Way, UMC 9700, North Logan, UT 84341-1947; Paul.Mueller@sdl.usu.edu), [2]Jet Propulsion Laboratory (4800 Oak Grove Drive, M/S 157-205, Pasadena, CA 91109; Donald.Rapp@jpl.nasa.gov).

The Sabatier/Electrolysis (S/E) process is an attractive approach to in situ propellant production (ISPP), and a breadboard demonstration of this process at Lockheed Martin Astronautics funded by JPL performed very well, with high conversion efficiency, and reliable diurnal operation. There is a net usage of hydrogen in the S/E process, and this has been the principal problem for this approach to ISPP.

Transporting the hydrogen to Mars and storing it for the length of time needed to convert it into water and methane is a formidable problem. We have investigated approaches for storing hydrogen cryogenically, both in the methane and oxygen tanks of the Mars Ascent Vehicle (MAV), as well as in a dedicated hydrogen tank on the Mars lander which supports the MAV. However, because of tight mass and volume margins on current models of the MAV, storage in the MAV tanks does not appear feasible.

Recent studies made by Barry Nakazono, Dan Thunnissen, and Carl Guernsey of JPL indicate that in an MSR mission scenario involving a Mars orbit rendezvous, docking and sample transfer to a separately launched orbiter, there is excess mass capability on the lander as well as on the trans-Mars cruise vehicle using a Delta III launch vehicle. Therefore, we are concentrating on use of a dedicated hydrogen storage tank on the lander. Depending on the upper stage and launch opportunity chosen, the Delta III can throw between 2000 and 2200 kg into trans-Mars trajectory. The maximum mass which can enter the Martian atmosphere behind a conventional aeroshell which fits in the Delta III shroud is about 1800 kg. Assuming a 100-kg cruise stage and 100 kg of margin, this leaves up to 200 kg of available mass in cruise for supporting hydrogen transport. Of the 1800 kg entry mass, using current best mass estimates for the aeroshell, lander propellant, lander system, ISPP conversion and power system, and the dry mass of the MAV, it appears that there a capability to put a dedicated hydrogen storage unit on the lander, weighing up to 200 kg. Thus we not only have 200 kg of mass available on the lander for hydrogen storage, but we have up to an additional 200 kg on the Mars cruise vehicle to support hydrogen transport to Mars. With these masses available, the S/E process appears to be feasible for the MSR mission scenario described. The limiting factor is available volume rather than mass.

Several approaches to minimize the lander hydrogen tank dimensions, while meeting mass constraints, were considered and the best approach was selected and further developed. Given that we can land this hydrogen-filled tank on Mars, we now have several options available for operation the S/E process. Trade studies are being conducted to determine whether accelerated water production and storage as liquid water is advantageous, as compared to steady daily conversion to methane and oxygen. An optimized scenario for operation of the S/E process using this hydrogen storage system will be presented. With these results, we now believe that the S/E process is ready for further development into a flight-like system for a Mars ISPP sample return mission.

MARS IN SITU PROPELLANT PRODUCTION (ISPP) ASSESSMENT.

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This study investigates the benefits of various in situ propellant production (ISPP) implementation strategies for near-term Mars missions to support an integrated Mars exploration program. Missions included in this assessment are a 2005 Mars Sample Return (MSR) without ISPP, 2007 MSR with ISPP, and a 2011 HEDS cargo flight. For each mission, three to seven ISPP implementation options are investigated, varying propellant, primary ISPP processing system, and power source selections. Evaluation criteria include cost, ISPP-imposed complexity, and technology development requirements. Costs are assessed based on detailed mission performance estimates accounting for mission phase durations, propulsion system design, propellant storage and boiloff, ISPP system design, and other flight system mass and performance properties. ISPP-imposed complexity separates three major areas impacted by ISPP system selection: (1) the primary ISPP processing system development, (2) the supporting power system, and (3) the propulsion engine, tankage, and storage system design. ISPP processing candidates include Zirconia Solid Oxide Electrolysis (SOE) to generate oxygen and Sabatier/Water Electrolysis (S/E) to produce oxygen and methane (consuming hydrogen supplied from Earth). Propellant candidates considered include NTO/MMH, LOX/N2H4, LOX/C3H8, and LOX/CH4 (at various mixture ratios). Advanced technology requirements are compared based on the estimated magnitude of all required technology developments for each of the three missions, taking into account schedule impacts to ensure readiness prior to need. Study results include a benefits comparison of ISPP implementation options for the 2005–2011 Mars mission set, identification of technology needs, and recommendations for a Mars ISPP technology development roadmap.

OXYGEN PRODUCTION AND SEPARATION FROM MARTIAN ATMOSPHERE BY THE RADIO-FREQUENCY DISCHARGE. L. Vuskovic, R. L. Ash, S. Popovic, T. Dinh, and A. Van Orden, Old Dominion University, Norfolk, Virginia 23529 e-mail: lxv100f@oduvm.cc.odu.edu

Included are the new results from the experiments on the radio-frequency discharge of Martian atmospheric gas and separation of oxygen from the gas mixture using a silver membrane [1]. The discharge was generated at simulated conditions of the Martian surface atmosphere. Background gas pressure was 6 to 7 Torr. Gas mixture contained 95.7% CO_2, 2.7% N_2, and 1.6% Ar.

Radio-frequency discharge was capacitively coupled. The discharge electrodes were in contact with the discharge. Both electrodes are made of silver. One of the electrodes was the thin silver membrane. It was used for extraction of atomic oxygen from the discharge gas mixture.

The efficiency of oxygen separation was tested as a function of the thickness of the silver membrane and the operating temperature. Quality of the separated oxygen depends on the isolation of the collection side and the reaction side of the system. The membrane structure must maintain oxygen flux, without penetration of other components of the residual gas mixture into the oxygen collection and storage space.

Two complementary approaches are currently being developed with the goal of obtaining high oxygen yield using the capacitively coupled radio-frequency discharge and silver membrane. Currently, self-supporting membranes of silver sheet with a thickness of the order of 0.1 mm are being tested. The second approach is in the development stage. It will permit the use of silver foils with thickness in the range of 1 μm. The foils will be supported with perforated silver sheets. It is expected that the second approach will achieve an oxygen extraction level close to the theoretical limit. Tests of durability of the membranes at high temperatures in the presence of the radio-frequency discharge are an important part of the present development activity.

The results of computer modelling show that the chemical composition of Martian atmospheric gas is changed by the radio-frequency discharge. Before entering the discharge, the Martian gas mixture contains predominantly carbon dioxide. In the discharge, the gas undergoes transformations involving many dissociation - recombination processes, as well as the diffusion of atomic oxygen through the silver membrane. The transformed gas mixture contains large proportions of carbon monoxide and oxygen with smaller amounts of carbon dioxide and other gases. Traces of water in the gas mixture contribute very effectively to recycling of carbon monoxide into carbon dioxide. The residual gas, after partial separation of oxygen, has a potential for further utilization, which we are currently investigating.

We will also present the preliminary design of the radio-frequency discharge cell to be used in the demonstration tests of oxygen production. The cell will be capable of processing a large volume of Martian atmospheric gas. It is designed to produce 1 to 3 g/h of pure oxygen, and about 1 l-atm/h of the residual gas, using the present level of silver membrane technology. We will describe the preliminary design of the oxygen extraction and storage system, based on the new radio-frequency discharge cell. The system will be designed to produce and store oxygen with the ambient parameters comparable to the other oxygen production systems. We anticipate that the test data on this system will provide a solid ground for scaling estimates. Using the results of laboratory tests, we will present estimates on the size, mass, power and efficiency of the radio-frequency discharge oxygen production systems, for oxygen production levels in the range between 0.01 and 1 kg/h.

In order to fully account for all aspects of Martian atmospheric conditions, part of our effort is focused on the long-term effects of Martian dust on the system. The property of the radio-frequency discharge to charge electrically, trap, and enable removal of dust particles will be described. It was found that the trapping of particles is size-selective. Particles with the smallest size tend to concentrate around the axis of the discharge, and the largest particles concentrate close to the discharge sheath. Silver membranes can repel the dust particles, since they are electrically charged in the plasma. The process has therefore an intrinsic mechanism of protection from contamination by dust particles.

References: [1] L. Vuskovic et al., SAE Paper 972499 (1997) and references therein.

INSITU PROPELLANT PRODUCTION BASED ON MICRO CHEMICAL SYSTEMS. R.S. Wegeng, W.E. TeGrotenhuis, and A.L.Y. Tonkovich, Pacific Northwest National Laboratory, P.O. Box 999, Richland WA 99352

Introduction: The development of compact processing hardware for the production of propellant fuels and oxygen from available resources on Mars or elsewhere presents a number of technical challenges including process miniaturization and thermal energy integration. Our approach to this problem consists of developing integrated reactors, heat exchangers, and separations units using microfabrication techniques that have the potential of realizing very compact systems with high throughputs and high thermal efficiencies.

Background: At the Department of Energy's Pacific Northwest National Laboratory, researchers have used precision engineering techniques, originally developed for the electronics industry, to fabricate and test a variety of microcomponents that perform many of the standard unit operations used in thermal and chemical process systems. This effort is now in its sixth year, and has reached the point where the development of integrated systems is underway for a number of applications.

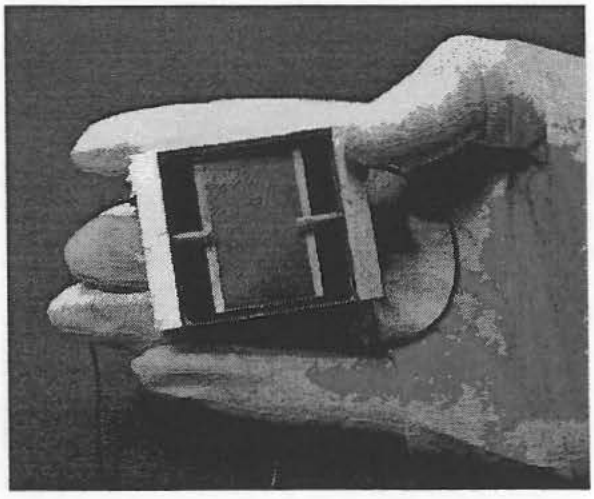
Advanced microcomponents currently in development include microchannel heat exchangers, gas absorbers, liquid-liquid extractors, reactors, and microactuators for pumps, valves and compressors. Systems performing chemical processing, power generation and refrigeration are also in development.

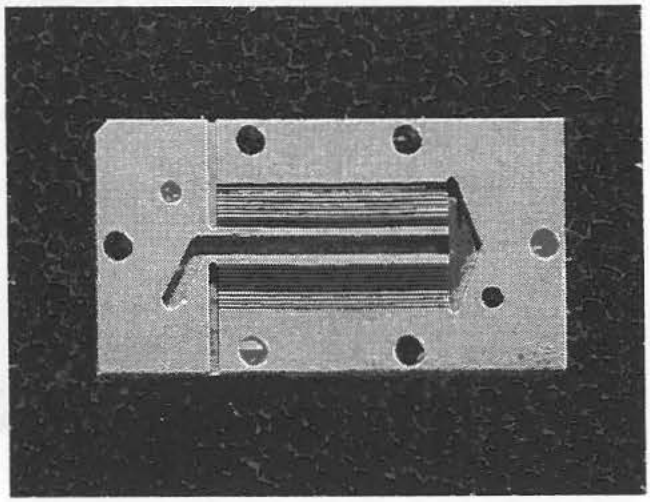
Heat and Mass Transport Advantages in Engineered Microstrutures: Heat and mass transfer is particularly rapid in systems utilizing engineered microchannels, and extraordinary performance has been demonstrated in microchannel heat exchangers, absorbers and reactors. For example, microchannel heat exchangers have been demonstrated with very high convective heat transfer coefficients (10,000 – 15,000 watts/m^2-K for single phase liquids, 30,000-35,000 watts/m^2-K for evaporating fluids).

A example of a microchannel heat exchanger is shown at lower left. Typical dimensions of microchannels are 100-300 microns wide and one to several millimeters deep, supporting heat fluxes exceeding 100 to 150 watts/cm^2. By themselves, microchannel heat exchangers are interesting articles that demonstrate how rapidly diffusion takes place across a thin fluid film; in combination with other microcomponents, new approaches to chemical processing problems are made possible.

Microchannel chemical reactors: We have shown that heterogeneous reactions with relatively fast intrinsic kinetics can be miniaturized with significant performance improvements in the reactor hardware. For example, we have conducted investigations involving the catalytic, partial oxidation of hydrocarbons in microchannel reactors (one element of this reactor is pictured at lower right) that demonstrate high conversions and selectivity for reaction products. Experiments with other reactors have demonstrated similar results.

Preliminary investigations have suggested that reactions of interest to NASA are good candidates for miniaturization using microfabrication techniques. For example, the Sabatier process, which produces methane and water from carbon dioxide and hydrogen, is an exothermic reaction with equilibrium limitations on the maximum conversion; at higher temperatures, lower conversions are obtained. For this reason, effective heat removal is needed in order to keep reaction temperatures down. It is therefore an





excellent candidate for development using an integrated microchannel reactor/heat exchanger approach.

Microchannel separations units: We are also investigating the development of novel separations systems based on microchannel architectures. For example, preliminary experimentation suggests that both solvent extraction and gas absorption are processes that can be enhanced through miniaturization. The former process being dominated by mass transport, and the latter being dominated by a combination of both heat and mass transport, microchannel test articles have preliminarily demonstrated the potential for high performance. Accordingly, our efforts are focused on the development of microchannel contactors that can reduce transport times (and therefore residence time requirements) by constraining transport distances to no more than a few hundred microns.

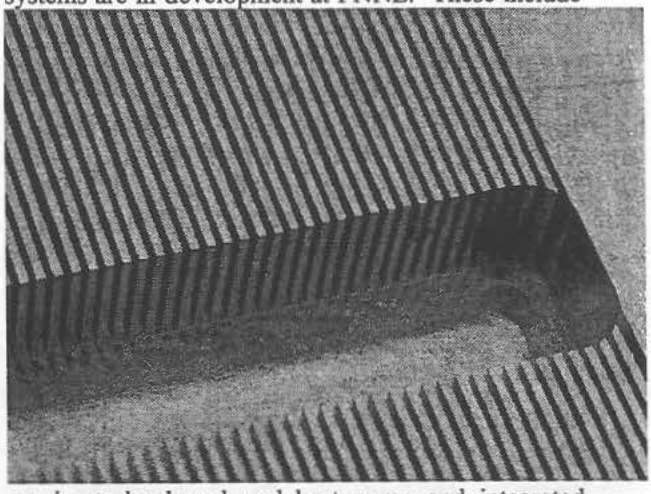
Other separations processes that are strong candidates for miniaturization include include gas adsorption and distillation. Over the next year, we intend to examine a number of ISPP separations needs, including separation of carbon monoxide and carbon dioxide, plus separation of water vapor from methane and from oxygen, to define the potential operational characteristics and advantages/disadvantages of employing a microtechnology approach to these needs.

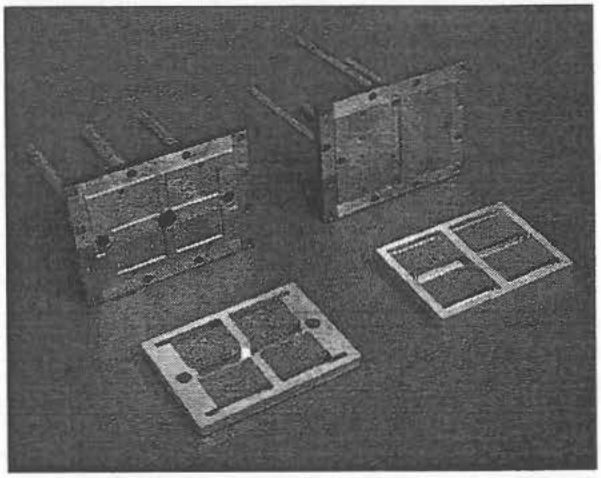
The development and scaleup of integrated micro chemical systems: As with the case of electronics, the scaleup of micro chemical systems is often made possible through the use of multiple components operating in parallel. This also provides potential advantages in terms of system reliability, redundancy, flexibility and operation.

A number of integrated, fullscale micro chemical systems are in development at PNNL. These include microchannel condensers and evaporators, plus a heat-actuated, thermochemical compressor, which in turn includes microchannel gas absorbers, desorbers, and heat exchangers. All of the components of the heat pump system have been demonstrated, and system level testing should be underway by November.

The fuel conversion components together will make up an onboard, automotive processing system for the production of hydrogen from liquid hydrocarbons. The hydrogen would then be used by onboard fuel cells for power generation. Reactors and heat exchangers in the system perform fuel vaporization, partial oxidation, water-gas-shift, and preferential oxidation reactions, and waste energy recovery operations. One component of the system, pictured at lower right, consists of four reactor and heat exchanger cells which operate in parallel, is only 1" by 3" by 4" in volume, and provides waste heat recovery and fuel vaporization functions for half of the fuel stream for the automobile.

Besides providing compact hardware solutions for individual ISPP components, the use of microsystemtechnologies may also provide an opportunity to improve overall system performance. For example, the inclusion of microchannel heat exchangers within individual components, including adsorbers, reactors and separations units, provides an opportunity for improved thermal integration. It is also possible that energy requirements for operating ISPP technologies could be reduced through the inclusion of microtechnology-based heat pumps, properly designed to operated between, say, an adsorption unit and a cryrogenic separations unit. We intend to attempt to identify and preliminarily characterize opportunities for such system advantages over the next year.





a microtechnology-based heat pump and integrated fuel conversion components. The heat pump employs

STAND-OFF PLANETARY SURFACE ANALYSIS USING LASER-INDUCED BREAKDOWN SPECTROSCOPY AND LASER-INDUCED PLASMA ION MASS SPECTROMETRY. R.C. Wiens, D.A. Cremers, J.D. Blacic, H.O. Funsten, and J.E. Nordholt, NIS-1, CST-1, EES-4, Los Alamos National Laboratory (Los Alamos, NM, 87545; rwiens@lanl.gov).

Introduction. Characterization of useable planetary materials will require high sampling throughput. Although *remote* observations from orbiting spacecraft provide spatially wide coverage, they do not, by themselves, provide sufficient information for materials utilization purposes. On the other hand, active rover-based *in-situ* analyses can provide detailed geological information but can be very time-consuming and limited in scope, as was recently demonstrated by the Mars Pathfinder Mission. The optimum configuration for detailed analysis with wide spatial coverage may be a *stand-off* technique.

Stand-off techniques are being tested which utilize laser interrogation for elemental and isotopic analyses. We are simultaneously testing both emission spectroscopy, to measure characteristic wavelengths in the laser-induced spark, and a mass spectrometer to measure the mass of ions generated and accelerated by the spark. Material can be analyzed from within a radius of several tens of meters from the instrument platform. A relatively large area can thus be sampled from a simple lander without requiring a rover or sampling arms. On a rover, such an instrument would allow sampling of locations not otherwise accessible, such as on a steep ledge, and its versatility would reduce travel requirements for the rover.

Emission spectroscopy of the laser-initiated spark can provide quantitative elemental abundances [1]. This method, commonly termed *laser-induced breakdown spectroscopy* (LIBS), has been studied for years but has only recently been adapted for practical applications. In the LIBS method, laser pulses are focused on a material to form laser plasmas, or sparks. These sparks are the result of emission from excited atoms ablated from the surface. Collection of the light, followed by spectral dispersion and detection, permits identification of the elements via their unique spectral signatures. When calibrated, concentrations can be determined. Because the laser plasma is formed by focused optical radiation, the method has several advantages over conventional elemental analysis methods. These include 1) rapid analysis, i.e. one measurement per laser pulse, 2) simultaneous multi-element detection, 3) ability to detect nearly all elements (high or low z), and 4) stand-off analysis capability [2]. Stand-off analysis is possible because the laser pulses can be focused at a distance to generate the plasma on a solid. The distances that can be achieved depend on the quality of the laser beam, the power density of the laser pulse, and the method used to focus the laser pulses on the target. Using pulses of 300 mJ having a 10 ns duration and a very simple four lens focusing system, the recording of spectra from geological samples has been demonstrated at distances up to 24 m. [3]. Measurements can be carried out with the sample in air or in a vacuum with equal results.

Mass spectrometry of the ionized plume from a laser is possible on airless bodies. Previous work in this area included a laser-

mass spectrometer package on the ill-fated Soviet Phobos missions. This instrument used the time-of-flight (TOF) from sample to spectrometer to determine the mass of the constituent ions, and was huge by today's standards--close to 1 m^3 and 80 kg [4]. Others have proposed similar instruments (e.g., [5]). However, this basic design has several drawbacks in addition to size. First, it is difficult to achieve high mass resolution due to a spread in initial energies from the laser spot. Secondly, multiply-charged ions are produced in abundance, and can cause significant interference, such as $^{56}Fe^{++}$ with $^{28}Si^{+}$, etc. An additional disadvantage common to most mass spectrometers is the interferences of various molecular and atomic species of the same mass. For example, no flight mass spectrometer has yet been able to determine high precision $^{18}O/^{16}O$ ratios on extraterrestrial material due to the ubiquitous presence of H_2O at mass 18.

These difficulties are overcome with a mass spectrometer design patented for space plasma physics applications [6,7]. This design separates molecules into their atomic constituents and analyzes the resulting singly-charged ions. The linear electric field segment of this instrument yields high resolution mass spectra based on time of flight, independent of initial ion energy. This design thus holds great potential for both elemental and high precision isotopic planetary materials analyses. Preliminary estimates [8] indicate that major and some trace element detection is easily feasible at a stand-off distance of 25 m.

Experiments are presently underway for quantitative LIBS elemental determinations at stand-off distances in a vacuum and at low pressures (e.g., 10 Torr) to simulate lunar and martian environments. Figures of merit include element detection limits and measurement accuracy and precision. Spares of the IMS (Cassini) and PEPE (DS-1) plasma mass spectrometers are in preparation for testing to determine ion yields of various materials and from that, reasonable stand-off distance capabilities. The two types of detectors are very complementary, as energy and mass information gleaned from the mass spectrometer can aid in calibrating matrix effects for optical spectroscopy, while elemental information from optical spectroscopy can aid interpretation of mass spectra. Work is progressing towards a valid flight prototype within a couple years. The present PEPE mass spectrometer is 5 W and 5 kg, including electronics. A flight-integrated optical detection system is estimated at < 1 kg, while a Nd-YAG laser system suitable for the above-mentioned distances is estimated at < 1 kg and < 1 W average power [3].

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Report on the Construction and Operation of a Mars *in situ* Propellant Production Unit Utilizing the Reverse Water Gas Shift. R. Zubrin, T. Kito, and B. Frankie, Pioneer Astronautics, 445 Union Blvd., Suite 125, Lakewood, CO 80228, 303-980-0890

This report describes work accomplished on a Mars in situ propellant production project utilizing the reverse water gas shift (RWGS) reaction. This project was carried out from March through September 1997 under NASA SBIR Phase I funding. John Connolly was the JSC program manager and Robert Zubrin was the principal investigator at Pioneer Astronautics. During the project, Pioneer successfully built and operated two chemical synthesis units representing the cores of machines capable of manufacturing oxidizer and a variety of fuels out of primarily indigenous Martian material. The units include a Reverse Water Gas Shift (RWGS) unit and a Methanol Synthesis (MEOH) unit.

The RWGS unit works in the following manner: Liquid hydrogen is transported from Earth to Mars, where it is combined with carbon dioxide acquired from the Martian atmosphere in a catalytic reactor to produce carbon monoxide and water. Water is condensed and separated from the gas phase. Unreacted feed components are compressed, recovered from the gas phase in a membrane unit separator, and recycled to the catalytic reactor. Effluent from the membrane unit ("retentate") is sent to the MEOH unit.

At H2/CO2 mixture ratios of 1:1 nearly all the hydrogen is reacted to make water, which can then be electrolyzed to produce oxygen and hydrogen, which can be recycled. Used in this way, the hydrogen brought to Mars can be recycled many times to produce an enormous amount of oxygen and CO. Alternatively, the feedstock to the RWGS can be run with an excess of hydrogen, resulting in RWGS effluent containing-both CO and H2. Such a mixture is known as synthesis gas and is the ideal feedstock for making methanol, dimethyl ether, or higher hydrocarbons

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The MEOH unit works in the following manner: Effluent from the RWGS unit, consisting primarily of CO with some residual unreacted hydrogen, is sent to a catalytic methanol synthesis reactor. The synthesis reactor combines one carbon monoxide molecule with two hydrogen molecules to produce methanol. Production from the methanol synthesis reactor is condensed and separated from the gas phase. Unreacted feed components are separated in a second membrane separator and recycled to the RWGS reactor feed. The second membrane retentate, consisting primarily of excess carbon monoxide, is vented from the system.

The MEOH unit was designed in a generic fashion so that different varieties of catalytic reactors could be tested without changing the process configuration. In addition to the methanol synthesis reactor, Pioneer experimented with a hybrid methanol/DME reactor and a Fischer-Tropsch hydrocarbon synthesis reactor.

Accomplishments during the Phase I project

Pioneer recorded a number of significant accomplishments during the project. Highlights include:

1) Development, manufacture, and demonstration of a catalyst which is 100% selective for the RWGS reaction at a wide range of conditions.
2) Design, construction and operation of a machine including a RWGS unit and a methanol synthesis unit.
3) Operation of the RWGS machine in oxygen production mode, attaining mass leverages in excess of 250.
4) Discovery that by altering the reactor temperature, pressure, and feed ratio, the RWGS unit could be run in combined Sabatier/RWGS mode with potential mass leverage of 20. Achieved an actual mass leverage during operation of 16.5, which compares to a 10.3 leverage for an S/E unit.
5) Operation of the machine in a mode to produce a combined 50/50 molar CH4/CO ratio fuel with a stoichiometric oxygen ratio. In this mode, the system demonstrated a mass leverage of 31 with a 23 excess oxygen mass leverage.
6) Demonstration of production of synthesis gas (syngas) feed for methanol, dimethyl ether (DME, =CH3OCH3), Sabatier, or Fischer-Tropsch reactors. The quality of syngas produced was sufficient to allow a methanol/O2 leverage of 16.3 or a Fischer-Tropsch/O2 leverage of 22.4.
7) Demonstration of production of a 79% methanol/ 21% water fuel product with no other contaminants.
8) Demonstration of conversion of 8% of the feed carbon dioxide to dimethyl ether (DME) in a one pass (no recycle) hybrid reactor.
9) Demonstration of conversion of at least 44% of the feed carbon dioxide to ethane or higher hydrocarbon species in a one pass Fischer-Tropsch reactor.
10) Demonstration of complete recovery of gaseous hydrogen in a two membrane loop system, with no gaseous hydrogen detected in the system vent.

In conclusion, we find that based on the work done to date, that the RWGS offers a feasible and potentially attractive method of performing in-situ propellant production on Mars and should be researched further.